

# A Thermodynamic History of the Solar Constitution — I: The Journey to a Gaseous Sun

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History has the power to expose the origin and evolution of scientific ideas. How did humanity come to visualize the Sun as a gaseous plasma? Why is its interior thought to contain blackbody radiation? Who were the first people to postulate that the density of the solar body varied greatly with depth? When did mankind first conceive that the solar surface was merely an illusion? What were the foundations of such thoughts? In this regard, a detailed review of the Sun's thermodynamic history provides both a necessary exposition of the circumstance which accompanied the acceptance of the gaseous models and a sound basis for discussing modern solar theories. It also becomes an invitation to reconsider the phase of the photosphere. As such, in this work, the contributions of Pierre Simon Laplace, Alexander Wilson, William Herschel, Hermann von Helmholtz, Herbert Spencer, Richard Christopher Carrington, John Frederick William Herschel, Father Pietro Angelo Secchi, Hervé August Etienne Albans Faye, Edward Frankland, Joseph Norman Lockyer, Warren de la Rue, Balfour Stewart, Benjamin Loewy, and Gustav Robert Kirchhoff, relative to the evolution of modern stellar models, will be discussed. Six great pillars created a gaseous Sun: 1) Laplace's Nebular Hypothesis, 2) Helmholtz' contraction theory of energy production, 3) Andrew's elucidation of critical temperatures, 4) Kirchhoff's formulation of his law of thermal emission, 5) Plücker and Hittorf's discovery of pressure broadening in gases, and 6) the evolution of the stellar equations of state. As these are reviewed, this work will venture to highlight not only the genesis of these revolutionary ideas, but also the forces which drove great men to advance a gaseous Sun.

## 1 On the history of solar science

Pondering upon the history of solar science [1–14], it becomes apparent that, in every age, the dominant theory of the internal constitution of the Sun reflected the state of human knowledge. As understanding of the physical world grew, the theories of old were slowly transformed. Eventually, under the burden of evidence, ancient ideas were destined to disappear completely from the realm of science, relinquished to the sphere of historical curiosity [2]. What was once considered high thought, became discarded.

If science is to advance, historical analysis must not solely reiterate the progress of civilization. Its true merit lies not in the reminiscence of facts, the restatement of ancient ideas, and the reliving of time. Rather, scientific history's virtue stems from the guidance it can impart to the evolution of modern research.

Historical compilations, dissected with contemporary scientific reasoning, have the power to expose both the truths and the errors which swayed our formation of a gaseous Sun [15–21]. These models have evolved as a direct manifestation of mankind's physical knowledge in the 19th and 20th centuries. Through historical review, it can be demonstrated that virtually every salient fact which endowed the Sun with a gaseous interior has actually been refuted or supplanted by modern science. Astrophysics, perhaps unaware of the histor-

ical paths followed by its founders [1–14], has at times overlooked the contributions and criticisms of “non-astronomers”. Perhaps unable to accept the consequences stemming from the discoveries of the present age, it has continued to perpetuate ideas which can no longer hold any basis in the physical world.

## 2 Pillars of a gaseous Sun

Five great pillars gave birth to the gaseous Sun in the middle and late 19th century. They were as follows: 1) Laplace's nebular hypothesis [22, 23], 2) Helmholtz' contraction theory [24, 25], 3) Cagniard de la Tour's discovery of critical phenomena [26, 27] and Andrew's elucidation of critical temperatures [28, 29], 4) Kirchhoff's formulation of his law of thermal emission [30–32], and 5) the discovery of pressure broadening in gases by Plücker, Hittorf, Wüllner, Frankland, and Lockyer [33–37]. Today, the last four of these pillars have collapsed, either as scientifically unsound (pillar 4), or as irrelevant with respect to discussions of the internal constitution of the Sun and the nature of the photosphere (pillars 2, 3, and 5). Only the first argument currently survives as relevant to solar theory, albeit in modified form. Nevertheless, each of these doctrines had acted as a driving force in creating a gaseous Sun. This was especially true with regards to the ideas advanced by Helmholtz, Andrews, Kirchhoff, and those

who discovered pressure broadening.

A careful scrutiny of history reveals that, beyond these factors, the greatest impulse driving mankind to a gaseous Sun was the power of theoretical models. In fact, given that all the great experimental forces have evaporated, astrophysics is left with the wonder of its theoretical formulations. Hence, a 6th pillar is introduced: the stellar equations of state [15–17]. It is an important foundation, one which remains intact and whose influence continues to dominate virtually every aspect of theoretical astrophysics.

### 2.1 Laplace's nebular hypothesis

Laplace's nebular hypothesis [22,23] was often proposed as a starting point for stellar formation in the 19th century. It became the seed for Helmholtz' contraction theory [24,25], as will be seen in Section 2.2. Laplace's hypothesis was based on the idea that the Sun and the solar system were created by the slow contraction of a nebulous mass. It was initially outlined in very general terms [38] by Emanuel Swedenborg [39, p. 240–272]. Swedenborg, a Swedish philosopher and theologian, believed himself capable of supernatural communication [40, p. 429]. He made numerous contributions to the natural sciences, but in astronomy, the ideas which brought forth the nebular hypothesis may not be solely his own. Rather, Swedenborg might have simply restated the thoughts of the ancient philosophers [2, 38–40]. Still, for the astronomers of the 19th century, Laplace's name stands largely alone, as the father of the nebular hypothesis.

At present, the Solar Nebular Disk Model (SNDM) [41] has largely replaced the nebular hypothesis, although it maintains, in part, its relationship with the original ideas of Laplace. Space limitation prevents our discussion of these concepts. The point is simply made that, despite the passage of more than two centuries, there remains difficulties with our understanding of the formation of the solar system, as Woolfson recalls: “*In judging cosmogonic theories one must have some guiding principle and that oft-quoted adage of the fourteenth-century English monk, William of Occam, known as Occam's razor, has much to commend it. It states ‘Essentia non sunt multiplicanda praeter necessitatem’ which loosely translates as ‘the simplest available theory to fit the facts is to be preferred’. The characteristics of the SNDM is that it neither fits the facts nor is it simple*” [42].

As for Laplace's nebular hypothesis, it was never specific to a particular solar phase (gas, liquid, or solid). Thus, even Kirchhoff had recourse to the ideas of Laplace in arguing for a solid or liquid photosphere [43, p. 23]. The theory could be applied to all solar models and finds prominence in many discussions of solar formation throughout the 19th century. Logically, however, the concept of a slowly contracting gaseous nebular mass enabled a continuous transition into Helmholtz's theory and the stellar equations of state. This was an aspect not shared by the liquid or solid models of the Sun. Hence, Laplace's ideas, though not counter to the liquid

or solid Sun, were more adapted to a gaseous solar mass.

### 2.2 Helmholtz' contraction theory

Helmholtz' great contraction theory dominated solar science almost since the time it was elucidated at a Königsberg lecture on February 7th, 1858 [24,25]. The mathematical essence of this lecture was rapidly reprinted in its entirety [24]. Prior to the birth of this theory, solar energy production was based on the meteoric hypothesis as introduced by J.R. Mayer [44], one of the fathers of the 1st law of thermodynamics [45]. The meteoric hypothesis was then championed by Lord Kelvin [46,47]. Hufbauer provided an excellent description of the evolution of these ideas [14, p. 55–57]. Despite the statures of Mayer [44,45] and Thomson [46,47], the meteoric hypothesis quickly collapsed with the dissemination of Helmholtz' work [24,25]. The contraction theory became a dominant force in guiding all solar models from the middle of the 19th century through the beginning of the 20th. Given the relative incompressibility of liquids and solids, Helmholtz' concepts were more compatible with the gaseous models. The 1660 law of Boyle [48] and the law of Charles [49], published in 1802 by Gay-Lussac, had just been combined into ideal gas law by Claperon in 1832 [50]. Consequently, it was more logical to assume a gaseous interior. Helmholtz' theory was consequently destined to prominence.

When formulating his contraction hypothesis, Helmholtz emphasized the contraction of nebular material, as advanced by Laplace [24, p. 504]. He stated: “*The general attractive force of all matter must, however, impel these masses to approach each other, and to condense, so that the nebulous sphere became incessantly smaller, by which, according to mechanical laws, a motion of rotation originally slow, and the existence of which must be assumed, would gradually become quicker and quicker. By the centrifugal force, which must act most energetically in the neighborhood of the equator of the nebulous sphere, masses could from time to time be torn away, which afterwards would continue their courses separate from the main mass, forming themselves into single planets, or, similar to the great original sphere, into planets with satellites and rings, until finally the principle mass condensed itself into the Sun*” [24, p. 504–505].

The contraction theory of energy production would not easily yield its pre-eminent position in solar science, surviving well into the 20th century. Still, practical difficulties arose with Helmholtz' ideas, particularly with respect to the age of the Earth. Eventually, the concept became outdated. Nuclear processes were hypothesized to fuel the Sun by Arthur Eddington in his famous lecture of August 24th, 1920 [51]. This dramatic change in the explanation of solar energy production [52] would produce no obstacle to maintaining a gaseous Sun. This was true even though Helmholtz' theory had been so vital to the concept of a gaseous interior, both in its inception and continued acceptance. Astrophysics quickly abandoned Helmholtz' contraction hypothesis and adopted an al-

ternative energy source, without any consequence for the internal constitution of the Sun. Ultimately, the advantages of condensed matter in solar fusion were never considered. This remained the case, even though the internuclear proximity within the solid or liquid might have held significant theoretical advantages for fusion when combined with the enormous pressures inside the Sun.

### 2.3 Andrews and critical temperatures

Addressing the role of Andrews and critical temperatures [28, 29] for solar theory, Agnes Clerke stated: “*A physical basis was afforded for the view that the Sun was fully gaseous by Cagniard de la Tour’s experiments of 1822, proving that, under conditions of great heat and pressure, the vaporous state was compatible with considerable density. The position was strengthened when Andrews showed, in 1869, that above a fixed limit of temperature, varying for different bodies, true liquefaction is impossible, even though the pressure be so tremendous as to retain the gas within the same space that enclosed the liquid*” [11, p. 188]. A. J. Meadows echoed these ideas when he later added: “*Andrews showed that there existed a critical temperature for any vapour above which it could not be liquefied by pressure alone. This was accepted as confirming the idea, evolved in the 1860’s, of a mainly gaseous Sun whose gas content nevertheless sometimes attained the density and consistency of a liquid*” [13, p. 30].

In the second half of the 19th century, the interior of the Sun was already hypothesized to be at temperatures well exceeding those achievable on Earth in ordinary furnaces. It became inconceivable to think of the solar interior as anything but gaseous. Hence, the gaseous models easily gained acceptance. Even today, it is difficult for some scientists to consider a liquid sun, when confronted with a critical temperature for ordinary hydrogen of  $-240.18\text{ C}$ , or  $\sim 33\text{ K}$  [53, p. 4–121]. In view of this fact, the existence of a liquid photosphere seems to defy logic.

However, modern science is beginning to demonstrate that hydrogen can become pressure ionized such that its electrons enter metallic conduction bands, given sufficiently elevated pressures. Liquid metallic hydrogen will possess a new critical temperature well above that of ordinary hydrogen. Already, liquid metallic hydrogen is known to exist in the modern laboratory at temperatures of thousands of Kelvin and pressures of millions of atmospheres [54–56]. The formation of liquid metallic hydrogen brings with it a new candidate for the constitution of the Sun and the stars [57–60]. Its existence shatters the great pillar of the gaseous models of the Sun which the Andrew’s critical point for ordinary gases [28, 29] had erected. It seems that the phase diagram for hydrogen is much more complex than mankind could have imagined in the 19th century. The complete story, relative to hydrogen at high temperatures and pressures, may never be known. Nevertheless, it is now certain: the foundation built by Andrews [28] has given way.

### 2.4 Kirchhoff’s law of thermal emission

Gustav Kirchhoff thought that the solar photosphere was either liquid or solid [43]. He based his belief on the continuous nature of the solar spectrum, adding that its generation by condensed matter was “*the most probable proposition*” [43]. In hindsight, Kirchhoff should have been even more forceful, as the existence of a continuous solar spectrum produced by condensed matter was indeed *the only possible proposition*. Kirchhoff held the answer in his hands nearly 150 years ago, but through the erroneous formulation [61–66] of his law of thermal emission [30–32] he allowed his insight on the state of the photosphere to be usurped by scientific error.

In speaking on the physical constitution of the Sun, Kirchhoff referred to his law of thermal emission in stating: “*for all bodies begin to glow at the same temperature. Draper has ascertained experimentally the truth of this law for solid bodies, and I have given a theoretical proof for all bodies which are not perfectly transparent; this, indeed, follows immediately from the theorem, concerning the relation between the power of absorption and the power of emission of all bodies*” [43, p. 26]. Of course, Kirchhoff’s extension of Draper’s findings from solid bodies to liquids and gases enabled the creation of a fully gaseous Sun in the 20th century. Kirchhoff’s law stated that, within an adiabatic or isothermal opaque cavity at thermal equilibrium, the radiation would always be represented by a universal blackbody spectrum whose appearance was solely dependent on temperature and frequency of observation, irrespective of the nature of the walls (provided that they were not transparent) or the objects they contained [30–32]. Kirchhoff’s law argued, by extension, that a gas could produce a continuous blackbody spectrum. Provided that the Sun could be conceived as following the restrictions for enclosure as required by Kirchhoff’s law, there could be no problems with a gaseous structure for the production of the continuous solar spectrum. As such, Kirchhoff had already condemned his liquid photosphere [43] three years earlier, when he formulated his “*law of thermal emission*” [30–32]. According to Kirchhoff’s law, liquids and solids were not required to obtain a blackbody spectrum. This unintended error would permeate physics throughout the next 150 years.

The problems with Kirchhoff’s law were not simple to identify [61–66] and Planck himself [67, 68] echoed Kirchhoff’s belief in the universal nature of radiation under conditions of thermal equilibrium [69, p. 1–25]. Planck did not discover Kirchhoff’s critical error. Furthermore, his own derivation of Kirchhoff’s law introduced arguments which were, unfortunately, unsound (see [61, 64, 65] for a complete treatment of these issues). In reality, the universality promoted by Kirchhoff’s law involved a violation of the first law of thermodynamics, as the author has highlighted [65, p. 6].

The acceptance of Kirchhoff’s law, at the expense of Stewart’s correct formulation [70], enabled the existence of a gaseous Sun. Its correction [61–66] immediately invalidates

the existence of a gaseous photosphere. Condensed matter is required to produce a continuous thermal spectrum, such as that emitted by the solar photosphere. Blackbody radiation was never universal, as Kirchhoff advocated [30–32] and much of astrophysics currently believes. If Kirchhoff's law had been valid, scientists would not still be seeking to understand the nature of the solar spectrum [71–73] after more than 150 years [74–76]. In reality, the most important pillar in the erection of a gaseous Sun was defective.

## 2.5 Pressure broadening

Despite the existence of Kirchhoff's law, physicists in the early 1860's understood that gases did not produce continuous spectra. Gases were known to emit in lines or bands. As a result, though Kirchhoff's law opened the door to a gaseous Sun, it was not supported by sound experimental evidence. It was under these circumstances, that the concept of pressure broadening in gases entered astrophysics.

In 1865, Plücker and Hittorf published their classic paper on the appearance of gaseous spectra [33]. They reported that the spectrum of hydrogen could assume a continuous emission as pressures increased: *“Hydrogen shows in the most striking way the expansion of its spectral lines, and their gradual transformation into a continuous spectrum... On employing the Leyden jar, and giving to the gas in our new tubes a tension of about 60 millims, the spectrum is already transformed to a continuous one, with a red line at one of its extremities. At a tension of 360 millims. the continuous spectrum is high increased in intensity, while the red line H $\alpha$ , expanded into a band, scarcely rises from it”* [33, p. 21–22]. Wüllner quickly confirmed pressure broadening in gaseous spectra [34,35]. Relative to hydrogen, he wrote: *“As the pressure increases, the spectrum of hydrogen appears more and more like the absolutely continuous one of an incandescent solid body”* [35].

During this same period, Frankland [36] and Lockyer made the critical transition of applying line broadening explicitly to the Sun [37]. Much of this discussion was reproduced in Lockyer's text [5, p. 525–560]. They proposed that pressure alone resulted in spectral broadening, excluding any appreciable effects of temperature. This was something which, according to them, had escaped Plücker and Hittorf [33]. They refuted Kirchhoff's solid or liquid photosphere: *“We believe that the determination of the above-mentioned facts leads us necessarily to several important modifications of the received history of the physical constitution of our central luminary — the theory we owe to Kirchhoff, who based it upon his examination of the solar spectrum. According to this hypothesis, the photosphere itself is either solid or liquid, and it is surrounded by an atmosphere composed of gases and the vapours of the substances incandescent in the photosphere... With regard to the photosphere itself, so far from being either a solid surface or a liquid ocean, that it is cloudy and gaseous or both follows both from our observations and*

*experiments”* [37].

Unfortunately, the concept that the spectrum of a gas can be pressure broadened had little relevance to the problem at hand. The line shape was not correct, though this difficulty escaped scientists of this period. The full solar spectrum was not available, until provided by Langley in early 1880's [71–73]. The spectrum of the Sun was not simply broadened, but had the characteristic blackbody appearance, a lineshape that gases failed to reproduce, despite the insistence of Kirchhoff's law to the contrary. In 1897, W.J. Humphreys published his extensive analysis of the emission spectra of the elements [77]. The work only served to re-emphasize that not a single gas ever produced a blackbody spectrum [67–69] through pressure broadening. As a result, the fifth pillar had never carried any real relevance to solar problems.

Hence, astrophysics has had to contend with the inability to generate a Planckian spectrum [67–69] from gases. The spectrum so easily obtained with graphite or soot [61, 65] remained elusive to gaseous solar models, unless recourse was made to a nearly infinite mixture of elemental species and electronic processes [74–76]. As a mechanism, pressure broadening would fall far short of what was required. *A priori*, it shared nothing with the fundamental mechanism existing in graphite and soot, the two best examples of true blackbodies in nature. Consequently, the intriguing discovery of pressure broadening in the 1860's has failed solar science. In reality, the search for the origin of the solar spectrum using gaseous emission spectra has continued to evade astrophysics until the present day, as evidenced by the very existence of The Opacity Project [74, 75].

## 2.6 The stellar equations of state

Many scientists have not recognized that a slow transformation is taking place in the physical sciences. In large part, this is due to the elegance of the stellar equations of state [15–21] as they continued to evolve from the seminal thoughts of Lane [78], Schuster [79, 80], Very [81], and Schwarzschild [82]. As such, astronomy continues to advocate a gaseous Sun. In doing so, it sidesteps the consequences of solar phenomena and attempts to endow its gaseous models with qualities known only to condensed matter. Simplicity beckons the liquid photosphere through every physical manifestation of its state [57–60]. But, solar physics remains bound by the gaseous plasma.

## 3 Historical account of the constitution of the Sun

### 3.1 William Herschel, speculation, and the nature of scientific advancements

Throughout scientific history, the nature of the Sun has been open to changing thought (see Table 1) and, in hindsight, often wild speculation. Even the strangest ideas of our forefathers possess redeeming qualities. It is almost impossible, for instance, to escape the intellectual delight which day-

author	year	sunspots	photosphere	solar body
Thales [5, p. 2]	600 B.C.	?	?	solid
Galileo [101, p. 124]	1612	clouds	fluid	?
Descarte [100, p. 147]	1644	opaque solid mass	fluid	fluid
de la Hire [98, p. 391]	1700	opaque solid mass	fluid	fluid
J. Lalande [98]	1774	opaque solid mass	fluid	fluid
A. Wilson [84]	1774	cavities in photosphere	fluid	dark and solid
W. Herschel [83]	1795	cavities in photosphere	luminous cloud layer	inhabited solid
W. Herschel [88]	1801	cavities in photosphere	luminous cloud/reflective cloud	inhabited solid
F. Arago [89, p. 29]	1848	openings in photosphere	gaseous	solid
J. Herschel [93, p. 229]	1849	cavities in photosphere	luminous cloud/reflective cloud	dark solid
H. Spencer [104, 105]	1858	cyclones	incandescent liquid	gaseous
G. Kirchhoff [43]	1862	clouds	incandescent liquid	solid or liquid
W. Thomson [47]	1862	?	incandescent liquid	incandescent liquid
A. Secchi [95, 96]	1864	openings in photosphere	gaseous with condensed matter	gaseous
J. Herschel [97]	1864	cavities in photosphere	gas?/vapour?/liquid?	dark solid
H. Faye [111, 112, 120]	1865	openings in photosphere	gaseous with condensed matter	gaseous
de la Rue, Stewart, Loewy [133]	1865	openings in photosphere	gaseous with condensed matter	gaseous
Frankland and Lockyer [37]	1865	openings in photosphere	gaseous with condensed matter	gaseous
H. Faye [119]	1872	cyclones	gaseous with condensed matter	gaseous
Modern theory	present	gaseous (magnetic fields)	gaseous	gaseous

Table 1: A partial summary of humanity's concept of the Sun.

dreams of William Herschel's 'solarians' invoke [83]. An inhabited solid solar surface might seem absurd by our standards, but such beliefs dominated a good portion of 19th century thought, at least until the days of Kirchhoff and the birth of solar spectral analysis [30–32, 43]. If Herschel's solarians are important, it is not so much because their existence holds any scientific merit. The solarians simply constitute a manifestation of how the minds of men deal with new information.

As for the concept that the Sun was a solid, the idea had been linked to Thales [5, p. 2], the Greek philosopher, who is said to have pondered upon the nature of the Sun in the 6th century B.C., although no historical evidence of this fact remains [2, p. 81–84]. Lockyer provided a brief discussion of ancient thought on the Sun [5, p. 1–12], in which we were reminded of the words of Socrates that “speculators on the universe and on the laws of the heavenly bodies were no better than madmen” [5, p. 5]. Relative to a solid Sun, Herschel did not deviate much from the thoughts of the ancient philosophers whose conjectures were, at times, fanciful [2].

With regard to the photosphere and the “outer layers of the Sun”, Herschel placed his distinct mark on solar science. In doing so, he built on the foundation advanced by his predecessor, Alexander Wilson, in 1774 [84]. Herschel wrote:

*“It has been supposed that a fiery liquid surrounded the sun, and that, by its ebbing and flowing, the highest parts of it were occasionally uncovered, and appeared under the shape of dark spots; and in that manner successively assumed different phases”* [83, p. 48] . . . *“In the instance of our large spot on the sun, I concluded from the appearances that I viewed the real solid body of the Sun itself, of which we rarely see more than its shining atmosphere. . . . The luminous shelving sides of a spot may be explained by a gentle and gradual removal of the shining fluid, which permits us to see the globe of the Sun”* [83, p. 51] . . . *“The Sun, viewed in this light, appears to be nothing else than a very eminent, large, and lucid planet, evidently the first, or in strictness of speaking, the only primary one of our system; others being truly secondary to it. Its similarity to the other globes of the solar system with regard to its solidity, its atmosphere, and its diversified surface; the rotation upon its axis, and the fall of heavy bodies, lead us to suppose that it is most probably also inhabited, like the rest of the planets, by being whose organs are adapted to the peculiar circumstances of that vast globe”* [83, p. 63].

Herschel believed that the Sun was a solid globe surrounded by a photosphere made from an elastic fluid which was responsible for light production: “An analogy that may

*be drawn from the generation of clouds in our own atmosphere, seems to be a proper one, and full of instruction. Our clouds are probably decompositions of some of the elastic fluids of the atmosphere itself, when such natural causes, as in this grand chemical laboratory are generally at work, act upon them; we may therefore admit that in the very extensive atmosphere of the sun, from causes of the same nature, similar phaenomena will take place; but with this difference, that the continual and very extensive decomposition of the elastic fluids of the sun, are of a phosphoric nature, and attended with lucid appearances, by giving out light”* [83, p. 59].

Though Herschel first described an inhabited star in 1795, he soon discovered infrared radiation [85–87] and realized that the Sun would provide an uncomfortable setting for its population. In a valiant attempt to save his solarians in 1801, Herschel advanced that the luminous layer of the photosphere, floating like a cloud above the solid solar surface, was positioned beyond an inferior reflective cloud which could channel the heat of the photosphere away from the inhabitants of the Sun [88]. Herschel incorporated a new fact, the discovery of infrared radiation [85–87], with a new concept, the reflective layer [88], in order to salvage an existing theory, the inhabited solid Sun [83]. A study of Herschel reminds us that theories are able to undergo many alterations in order to preserve a central idea, even if the sum of new facts has, long ago, shattered its foundation.

### 3.2 Alexander Wilson’s queries and conjectures

It is noteworthy that, unlike William Herschel, Alexander Wilson, in 1774 (see Table I), displayed uncharacteristic caution for speculation. In elucidating his ideas about the constitution of the Sun, the great astronomer placed the entire text in a section devoted to “*Queries and Conjectures*” [84, p. 20–30]. In fact, he dismissed much of the work of his predecessors as hypotheses without sound scientific basis. He was cautious to highlight the speculative nature of his theory on the constitution of the Sun when he wrote: “*When we consider, that the solar spots, some of whose properties have just now be enumerated, are so many vast excavations in the luminous substance of the Sun, and that, wherever such excavations are found, we always discern dark and obscure parts situated below; is it not reasonable to think, that the great and stupendous body of the Sun is made up of two kinds of matter, very different in their qualities; that by far the greater part is solid and dark; and that this immense and dark globe is encompassed with a thin covering of that resplendent substance, from which the Sun would seem to derive the whole of its vivifying heat and energy? And will not this hypothesis help to account for many phaenomena of the spots in a satisfactory manner? For if a portion of this luminous covering were by means displaced, so as to expose to our view a part of the internal dark globe, would not this give the appearance of a spot?*” [84, p. 20]. He continues: “*And from this may we not infer, that the luminous matter gravitates,*

*and is in some degree fluid. . .*” [84, p. 22]. Wilson brought forth a solid solar body surrounded by a gaseous or liquid photosphere. He was well aware of the limitations of his own knowledge relative to the photosphere, stating that: “*we may never have a competent notion of the nature and qualities of this shining and resplendent substance. . .*” [84, p. 21]. Wilson was prudent in the manner by which he proposed new ideas. He closed his address by stating with respect to “*many such other questions, I freely confess, that they far surpass my knowledge*” [84, p. 30]. At the same time, Wilson wrote his “*Queries and Conjectures*” precisely because he realized that they formed a basis for further discovery and questioning. In a field as complex as astronomy, devoid of direct contact with the subject of its attention, mankind could adopt no other logical course of action.

### 3.3 François Arago, John Herschel, and the constitution of the Sun in the mid-1800’s

By the middle of the 19th century, there seemed to have evolved both a popular conception of the Sun and a more “scientific” outlook. François Arago [89, 90], the premier astronomer in France during this period, shed light on the growing divide between popular thought and professional astronomy. He discussed the constitution of the Sun in these terms: “*Many conjectures have been offered in explanation of these spots. Some have supposed that the Sun, from which so vast a quantity of light and heat is incessantly emanating, is a body in a state of combustion, and that the dark spots are nothing else than scoriae floating on its surface. The faculae, on the contrary, they suppose due to volcanic eruptions from the liquified mass. The grand objection to this hypothesis is, that it does not suffice to explain the phenomena: it has not obtained admission among astronomers. The opinion most in favor in the present day, regards the Sun consisting of an obscure and solid nucleus, enveloped by two atmospheres — the one obscure, the other luminous. In this case, the appearance of the spot is explained by ruptures occurring in the atmosphere, and exposing the globe of the Sun to view. . .*” [89, p. 29].

Arago’s position constituted essentially a restatement of William Herschel [88]. Only the solarians seemed to have disappeared and the inner atmosphere became obscure, rather than reflective. In order to strengthen his position, Arago then added: “*This opinion, however strange it may appear, has the advantage of perfectly explaining all the phenomena, and it acquires a high degree of probability from the consideration, that the incandescent substance of the Sun cannot be either a solid or a liquid, but necessarily a gas*” [89, p. 29]. Arago justified his position for a gaseous photosphere, well ignorant of the discoveries to come, both of his own time and in the years to follow. He stated: “*It is an established fact that rays of light, issuing from a solid or liquid sphere in a state of incandescence, possess the properties of polarization, while those emanating from incandescent gases are devoid of them*” [89,

p. 29]. He immediately emphasized that polarization experiments support this position affording “*proof that the light of the Sun’s edges is as intense as that at its center*” [89, p. 29]. Further, “*But from the fact that the light from the edges of the Sun’s disk is as intense as that from the center, there follows another consequence; namely, that the Sun has no other atmosphere outside the luminous one; for otherwise the light of the edges, having a deeper layer to penetrate, would be found more weakened*” [89, p. 29].

Of course, François Arago was incorrect in stating that “*light of the Sun’s edges is as intense as that at its center*” [85, p. 29]. In fact, the converse was first observed in the days of Galileo [7, p. 274]. Arago’s contemporary, Sir John Herschel, wrote: “*The deficiency of light at the borders of the visible disc is in fact so striking, whether viewed through coloured glasses or without their intervention, by projecting its image through a good achromatic telescope on white paper, that it seems surprising it should ever have been controverted*” [91, p. 434]. Yet, Arago had the notion that a difference in path length through gas would account for differences in observed solar brightness. This was not far removed from the modern concept of optical depth which explained the same phenomenon [79–82, 92]. However, in this instance, it is the light visualized from the center of the Sun which is from deeper, and therefore warmer, regions. For modern solar astronomy, differing path lengths into the Sun permit the sampling of warmer areas. In any case, Arago’s arguments, relative to polarization as restated in his *Popular Astronomy* [90, p. 457], would be eventually refuted (see below).

As for John Herschel [91, 93, 94], over most of the course of his life, he viewed the constitution of the Sun through the eyes of his father, William: “*But what are the spots? Many fanciful notions have been broached on this subject, but only one seems to have any degree of physical probability, viz. that they are the dark, or at least comparatively dark, solid body of the Sun itself, laid bare to our view by those immense fluctuations in the luminous regions of its atmosphere, to which it appears to be subject*” [93, p. 229]. He stated that the “*more probable view has been taken by Sir William Herschel, who considers the luminous strata of the atmosphere to be sustained far above the level of the solid body by a transparent elastic medium, carrying on its upper surface. . . a cloudy stratum which, being strongly illuminated from above, reflects a considerable portion of the light to our eyes, and forms a penumbra, while the solid body shaded by the clouds, reflects none*” [93, p. 229]. The same citation can be found in the 10th edition of his work, published in 1869 [94, p. 314–315]. However, in 1864, along with Father Angelo Secchi [95, 96], John Herschel became one of the first professional astronomers to advance the concept that the Sun was gaseous when discussing sunspots in April of that year: “*while it agrees with that of an aggregation of the luminous matter in masses of some considerable size, and some degree of consistency, suspended or floating at a level determined by their . . . gravity*

*in a non-luminous fluid; be it gas, vapour, liquid, or that intermediate state of gradual transition from liquid to vapour which the experiments of Gagniard de la Tour have placed visibly before us*” [97]. In so doing, John Herschel was the first to propose that critical phenomena [26–29] may be important in understanding the structure of the Sun [57]. Oddly, he did not deem these ideas of sufficient merit to modify his popular text. In a public sense, John Herschel remained faithful to his father, even though nearly seventy years had elapsed in the “progress” of science.

### 3.4 Early thoughts of a fluid Sun

Unlike Alexander Wilson [84] and William Herschel [83, 88], who both advocated a solid solar body, the French astronomer Joseph Jérôme Le Français de Lalande thought that the Sun was a fluid. In his *Abrégé d’astronomie* of 1774 [98], Lalande reiterated the sentiment of his French predecessor, M. de la Hire. In 1700 and 1702, de la Hire stated that a sunspot was most likely the result of “*protrusion of a solid mass, opaque, irregular, swimming in the fluid material of the Sun, in which it sometimes dove entirely*” [98, p. 391]. René Descartes [99, 100] expressed essentially the same ideas in his *Principia Philosophiae*, published in 1644 [100, p. 147–152]. Descartes’ contributions were outlined in Karl Hufbauer’s classic text [14, p. 21].

Lalande also described how Galileo and Johannes Hevelius viewed the Sun as a fluid: “*Galileo, who was in no manner attached to the system of incorruptibility of the heavens, thought that Sun spots were a type of smoke, clouds, or sea foam that forms on the surface of the Sun, and which swim on an ocean of subtle and fluid material*” [98, p. 390–391]. In 1612, Galileo wrote: “. . . I am led to this belief primarily by the certainty I have that that ambient is a very tenuous, fluid, and yielding substance from seeing how easily the spots contained in it change shape and come together and divide, which would not happen in a solid or firm material” [101, p. 124]. Galileo differed from Lalande in advancing that sunspots were gaseous or cloudy versus solid [101, p. 98–101]. But, Galileo was not attached to this aspect of his work: “*for I am very sure that the substance of the spots could be a thousand things unknown and unimaginable to us, and that the accidents that we observed in them—their shape, opacity, and motion—being very common, can provide us with either no knowledge at all, or little but of the most general sort. Therefore, I do not believe that the philosopher who was to acknowledge that he does not and cannot know the composition of sunspots would deserved any blame whatsoever*” [101, p. 98]. It was the act of locating the spots on, or very close to, the surface of the Sun, that Galileo held as paramount [101, p. 108–124]. Thus, Galileo refuted Scheiner: “*I say that for the present it is enough for me to have demonstrated that the spots are neither stars, nor solid matters, nor located far from the Sun, but that they appear and disappear around it in a manner not dissimilar to*

that of clouds” [101, p. 294–295]. Scheiner, Galileo’s constant detractor, believed that special stars strangely coalesced to create sunspots [101, p. 98].

### 3.5 Kirchhoff, Magnus, Kelvin, and the liquid photosphere

In 1862, Gustav Kirchhoff elucidated the idea of a solid or liquid photosphere: *“In order to explain the occurrence of the dark lines in the solar spectrum, we must assume that the solar atmosphere incloses a luminous nucleus, producing a continuous spectrum, the brightness of which exceeds a certain limit. The most probable supposition which can be made respecting the Sun’s constitution is, that it consists of a solid or liquid nucleus, heated to a temperature of the brightest whiteness, surrounded by an atmosphere of somewhat lower temperature. This supposition is in accordance with Laplace’s celebrated nebular-theory respecting the formation of our planetary system”* [43, p. 23]. Kirchhoff explained how the Sun, like the planets, was formed through contraction. The Sun remained at the temperature of “white heat” as a result of its greater mass. Kirchhoff cited Arago extensively and was well aware of the work on sunspots by Alexander Wilson. Since the photosphere acted on the body of the Sun, Kirchhoff argued that it must also be heated to the point of incandescence. Relative to the constitution of the Sun, Kirchhoff’s entire driving force was the solar spectrum itself. The argument must be echoed, even in the present day.

Unfortunately, it was in speaking of sunspots that Kirchhoff confused the issue: *“But the phenomena exhibited by the solar spots, for whose benefit the hypothesis of a dark solar nucleus was started, may, I believe, be explained more completely and more naturally by help of the supposition concerning the constitution of the sun, which the consideration of the solar spectrum has led me to adopt”* [43, p. 26]. Kirchhoff then advanced that sunspots were the results of layers of clouds which cut off the heat emitted by the incandescent surface of the Sun. Kirchhoff’s thoughts were reminiscent of Galileo’s [101, p. 98–101], a point not missed by Secchi [3, p. 16], and Faye [5, p. 51–61]. Therefore, Alexander Wilson’s cavities were replaced by clouds. Kirchhoff invoked Secchi’s work and convection currents to explain why sunspots appear only at certain latitudes and tried to bring understanding to the origin of faculae. This entire portion of the text was somewhat nebulous in logic for a man like Kirchhoff. It would undermine his idea that the photosphere must be solid or liquid based on its continuous spectrum [43].

As an expert in thermal emission, Kirchhoff rapidly objected to Arago’s polarization arguments against the liquid. Emphatically, he maintained that Arago’s *“statement that incandescent gas is the only source of non-polarized light, is, however, incorrect, for Arago himself mentions that the common luminous gas-flame emits perfectly unpolarized light; and the light in this case is almost entirely caused not by glowing gas, but by incandescent particles of solid carbon*

*which are liberated in the flame. An incandescent haze consisting of solid or liquid particles must act in a manner precisely similar to such a flame”* [43, p. 30]. Kirchhoff further explained that a liquid Sun, whose seas are in continuous motions, would emit light from its surfaces in different directions with respect to our eyes. This destroyed any polarization. The argument was a powerful one, but as will be seen below, it was Kirchhoff’s explanation of sunspots which his contemporaries, Secchi and Faye, would reject. In so doing, they would dismiss Kirchhoff’s entire vision for the constitution of the Sun. This move on their part reflected, perhaps, their all too hasty conclusions with regards to thermal emission. The error continued to this day.

Heinrich Gustav Magnus [102] also believed that the Sun was a liquid. He was a great supporter of Kirchhoff [43]. On July 11th, 1861, he delivered Kirchhoff’s memoire on the chemical constitution of the Sun’s atmosphere before the Berlin Academy [103, p. 208]. Magnus demonstrated that the addition of caustic soda (sodium hydroxide) to a non-illuminating gaseous flame generated a tremendous increase in its luminosity [102]. He noted the same effect for the salts of lithium and strontium. In 1864, according to Magnus: *“These studies demonstrate that gaseous bodies emit much less heat radiation than solid or liquid bodies; and that, by consequence, one cannot suppose that the source of solar heat resides in a photosphere composed of gas or vapours”* [102, p. 174]. Magnus’ argument was powerful and, for the next 50 years, it continued to impact the constitution of the Sun. It was because of Magnus that photospheric theory would preserve some aspects of condensed matter well into the beginning of the 20th century. It would eventually take the theoretical arguments of men like Schuster [79,80], Very [81], Schwarzschild [82], Eddington [51], and Milne [92] to finally set aside Magnus’ contributions [102] and cast the concept of condensed matter out of the photosphere [43].

Kirchhoff liquid Sun was also echoed by William Thomson himself. Lord Kelvin states: *“It is, however, also possible that the Sun is now an incandescent liquid mass, radiating away heat, either primitively created in his substance, or, what seems far more probable, generated by the falling in of meteors in past times, with no sensible compensation by a continuance of meteoric action”* [47]. By the time these words were written, Thomson no longer believed that the Sun could replenish its energy with meteors and wrote: *“All things considered, there seems little probability in the hypothesis that solar radiation is at present compensated, to any appreciable degree, by heat generated by meteors fallings in; and, as it can be shown that no chemical theory is tenable, it must be concluded as most probable that the Sun is at present merely an incandescent liquid mass cooling”* [47]. In the same paper, Thomson discussed Helmholtz’ contraction theory, as an extension, it seemed, of the meteoric hypothesis [47]. The contraction and meteoric models of energy generation would eventually prove to be unsound. But, for the



time being, Thomson continued to view the Sun as liquid in nature, as did Kirchhoff and Magnus.

At the same time, it is ironic how Kirchhoff, through his law of thermal emission, unknowingly provided for astrophysics the very basis for the downfall of his liquid model. Currently, the entire concept of a gaseous Sun rests on the presumed validity of Kirchhoff's formulation. Nonetheless, early gaseous models of the Sun always placed either solid or liquid constituents in the region of the photosphere, as shall soon be outlined. Not until the early 20th century would the Sun become fully divested of condensed matter. In so doing, astrophysics would endow the gaseous plasma with emission properties it failed to possess on Earth. Regrettably, few of Kirchhoff's contemporaries supported his idea that the Sun was a liquid. Visual observations, and the view that Kirchhoff was an outsider to astronomy, would become ruinous to his model. Critical temperatures [28] also dictated that the Sun was simply too hot to allow this phase. Spectroscopic evidence became of secondary importance and the journey to a gaseous Sun formally began.

## 4 On to a gaseous Sun

### 4.1 Men, ideas, and priority

Throughout the history of astronomy, there is perhaps no more controversial figure than Herbert Spencer. As an independent philosopher, not formally trained in science, he became the first to advance that the interior of the Sun was completely gaseous [104–106]. He was also a staunch supporter of evolution and elucidated the concept of “*survival of the fittest*” [107]. In academic circles, Spencer was widely criticized for the views he held, both in ethics and in sociology [108]. By his supporters, he seemed highly admired [108] and compared to other polymaths including the likes of Goeth, Humbolt, and Whewell [103, p. 198]. Unfortunately, many of Spencer's social thoughts were unfounded and promoted concepts of imperialistic superiority and outright discrimination [107, p. 481–483]. His contributions on the constitution of the Sun [104, 105] were essentially ignored by professional astronomy, even though he corresponded with Sir John Herschel and Sir George Airy, the Astronomer Royal [106]. In addition, Spencer was a close friend of the great physicist John Tyndall who became, in like manner, a prominent evolutionist [106]. Spencer's political and social views were so counter to those espoused by men of the period that he remained ever outside the mainstream of astronomy.

Spencer eventually argued for priority over Hervé Faye with respect to his ideas of a gaseous Sun [105]. His defense was in response to review articles by Norman Lockyer published in the magazine *The Reader* [109, 110], about the Frenchman's *Comptes Rendus* papers [111, 112]. Nine years later, Lockyer reprinted these articles in his classic text [5, p. 44–62], without reference to Spencer's letter [105]. In doing so, Lockyer approached misconduct. He added a footnote

crediting Balfour Stewart and Gustav Kirchhoff for a thermodynamic argument which the record well demonstrated was first expounded in Spencer's letter, as will be discussed in Section 4.6 [105]. But since Lockyer was the cause of Spencer's 1865 letter [105], he could not have been unaware of its contents.

Bartholomew advanced a somewhat disparaging analysis of Spencer's contributions to solar physics [106]. He attempted to justify Spencer's rejection by professional astronomy. Though he gave Spencer qualities, he charged him with being simply an amateur, a surprisingly desultory reader, and of incorporating in his own writings facts and ideas acquired in other ways [106]. He even accused Spencer with making the Nebular hypothesis the starting point of his discussion, justifying the same behavior by men like Kirchhoff and Faye as merely supportive and confirmatory [106, p. 22]. Though Bartholomew brought forth several other reasons why Spencer was ignored, many of which were perhaps valid, his central argument was summarized as follows: “*Rather, at the mid-nineteenth century a criterion of acceptability for scientific pronouncements was beginning to emerge that was linked to the notion of professionalism; only those who had credentials in their subject through training and research could expect to have their speculative theories taken seriously. As this standard gradually asserted itself, Spencer's work in astronomy lost much of its claim for attention*” [106, p. 21]. This aspect of 19th century thought, beginning to permeate science in Spencer's day, had also been proposed while discussing Robert Chambers' *Vestiges on the Natural History of Creation* which was one of the first works on evolutionary reasoning: “*the reaction to Vestiges was not simply a profession of empiricism: it was an attempt to restrict the privilege of theoretical speculation to a small circle of recognized researchers*” [113, p. 22].

Relative to the Sun, a review of the documents of the period showed no more theoretical brilliance in the works of Secchi [95, 96, 114–118] and Faye [109–112, 119, 120] than in those of Spencer [104, 105]. This was reality, despite the fact that Spencer was charged with being ill-trained in thermodynamics, astronomy, and mathematics [106]. While Secchi was a magnificent observational astronomer [3], all three men were profoundly mistaken in many of their ideas regarding the Sun and sunspots. Furthermore, in light of modern analysis, their differences hinged on the trivial. Few of the early works of either Secchi or Faye were mathematical in nature [95, 96, 109–112, 114–120].

The nature of sunspots had immediately become a focus of contention between Spencer [105] and Faye [120]. In fact, Secchi and Faye would criticize Kirchhoff on the same subject, although they were far from being his equal in theoretical prowess. In *Comptes Rendus*, the battle between Faye and Kirchhoff on sunspots was protracted, extensive [121–126], and would yield many of the modern ideas for a gaseous Sun. Faye and Secchi's defense against Kirchhoff was some-

what justified, relative to sunspots not resting as clouds above the photosphere. But they did not sufficiently appreciate the importance of the German's arguments for condensed matter [43]. For many decades, the contributions of these two men, on the constitution of the Sun, were highly cited and praised. Spencer, their British colleague, continued to be essentially ignored [106].

Consequently, had the scientific community merely erected a means of self-promotion and preservation, with respect to theoretical speculation, by rejecting Spencer's work? This is unlikely to be the only explanation. It was obvious that many despised Spencer's social, ethical, and evolutionary thoughts. Competitive pressures must also have been involved. Hervé Faye clearly became acquainted with Spencer's work, given the three articles presented in *The Reader*. Still, the Frenchman long delayed to cite Spencer. Yet, it was unlikely that mere "scientific exclusivity" could account for Faye's and Lockyer's treatment of Spencer, as Bartholomew proposed. Hervé Faye defended religion and argued on moral grounds against the merits of evolution in addressing both science and God in his classic text which emphasized: "*Coeli enarrant gloriam Dei*" [127, p. 1–4]. As such, it appears that Faye consciously refused to confer upon Spencer the credit he deserved. This was especially true given the struggle for priority and Faye's time in history [127, p. 1–4]. The situation was perhaps clearer for Father Secchi. Secchi likewise echoed "*Coeli enarrant gloriam Dei*" [128, p. 1] and, on his deathbed, paraphrased Saint Paul (2 Timothy 4:7–8): "*I have finished my course, I have fought the good fight. Throughout my entire life and in my scientific career, I have had no other goal but the exultation of the Holy Catholic Church, demonstrating with evidence how one can reconcile the results of science with Christian piety*" [128, p. vii]. It must be remembered that, when the Jesuits would be expelled from Rome, Secchi was defended by the world scientific community. Only Secchi, with his assistants, was allowed to remain in the city and continued to work at the Observatory of the Roman College [128, p. xxii–xxiii]. Did Secchi know in advance of Spencer's *Westminster Review* article [104]? In 1869, Secchi had mentioned, with respect to Lockyer, that "*As to what regards his work, I admit that I have knowledge of only those which were published in Comptes Rendus, or in Les Mondes*" [5, p. 500]. The situation is not definitive however, as Secchi does mention his knowledge of the recent work by William R. Dawes in *Monthly Notices* in his first letter [95]. Nonetheless, it was doubtful that the Director of the Observatory of the Roman College knew of Spencer's works when he wrote his key papers of 1864 [95, 96]. The surest evidence was the lack of similarity between the ideas of Secchi [95, 96] and Spencer [104]. Conversely, this was not the case for Faye's classic papers [111, 112], including those dealing with the defense of his sunspot theory [119–126]. The problem for Faye would be three fold: 1) extensive scientific similarity, 2) eventual and certain knowledge of Spencer's

rebutal letter in *The Reader* [105] and 3) his claim of simultaneous discovery with respect to Secchi, as will be soon discovered. For Faye at least, it is difficult to argue against deliberate scientific disregard relative to Spencer and his ideas.

Relative to issues of faith, it is also notable that many learned men of the period shared Faye's and Secchi's dual affection for religion and science. In fact, even Max Planck would be counted in their company [129]. Bartholomew failed to address any of these points. It is unlikely that the dismissal of Spencer can be solely attributed to his lack of training, amateur status, and "*an attempt to restrict the privilege of theoretical speculation to a small circle of recognized researchers*" [113, p. 22]. The reality remained that some of Spencer's ideas continued to be objectionable (e.g. [107, p. 481–483]) and that the quest for priority was powerful.

Nonetheless, one must question the persistent failure [7, 13, 14] to give Spencer credit for advancing the earliest model of the gaseous Sun. Bartholomew's discussion [106], in trying to justify the past with the privilege of scientific position and "right to speak", did nothing to advance truth. This was especially highlighted, when contrasted with Galileo's free acknowledgement of Benedetto dei Castelli's contributions to the projection of sunspots [101, p. 126]. It was further expounded by the remembrance of Charles' law by Gay-Lussac [49], even though the former had not written a single word and the experiments were done fifteen years earlier. If the name of *Charles' law* exists, it is only because of Gay-Lussac's profound honesty. As such, the refusal to credit Spencer for his contributions should not be justified by modern writers [106], but rather, must be condemned as an unfortunate injustice relative to acknowledging the genesis of scientific ideas [130]. The reality remains that the birth of a gaseous Sun was accompanied by bitter rivalry throughout professional astronomy, much of which was veiled with struggles for priority. In this expanded context, and given his social views, Spencer's isolation was not surprising.

#### 4.2 Herbert Spencer and the nebular hypothesis

In reality, Spencer's contributions were noteworthy for their dramatic departure from the ideas of Herschel and Arago (see Table 1). Much like other works of the period, Spencer's thesis contained significant scientific shortcomings. Still, his writings were on par with those of his contemporaries and were, it appears without question, the first to outline both a gaseous solar body and a liquid photosphere. Spencer advanced this model in an unsigned popular work entitled *Recent Astronomy and the Nebular Hypothesis* published in the *Westminster Review* in 1858 [104]. He began his thesis by imagining a "*rare widely-diffused mass of nebulous matter, having a diameter, say as great as the distance from the Sun to Sirius*" [104, p. 191] and considered that mutual gravitation would eventually result in the "*slow movement of the atoms towards their common center of gravity*" [104, p. 191]. He argued that, as the nebular mass continued to contract, some

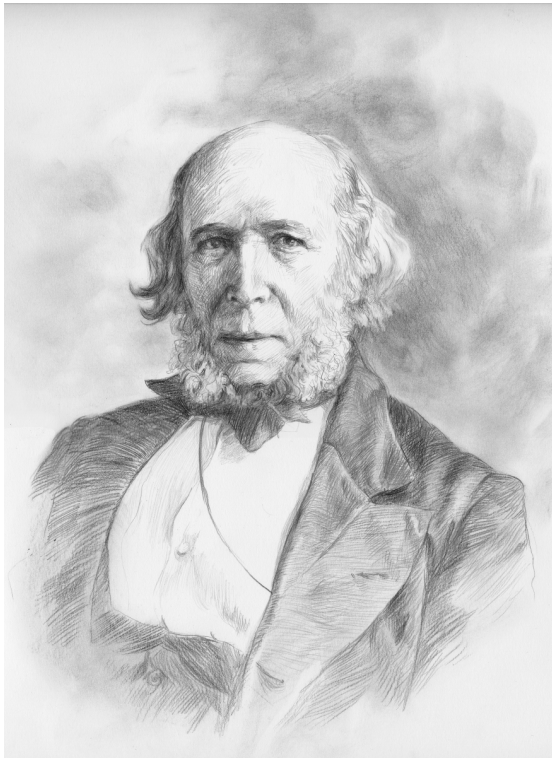


Fig. 1: Herbert Spencer (April 27th, 1820 — December 8th, 1903), was a polymath who advanced the first gaseous model of the Sun, in 1858 [104]. He conceived of a “Bubble Sun”, a gaseous interior of variable density surrounded by a fully liquid photosphere. (Drawing by Bernadette Carstensen — used with permission.)

of the internally situated atoms entered into chemical union. With time, as the heat of chemical reaction escaped the nebular mass, the latter began to cool. The binary atoms would then precipitate and aggregate into “*floculi*” [104, p. 192]. Spencer described how *floculi* formation resulted in centripetal motion of the nebula and eventually condensed into a larger internal and external aggregate masses. The latter developed into planets and comets. Spencer summarized Laplace’s nebular hypothesis as follows: “*Books of popular astronomy have familiarized even unscientific readers with his [Laplace’s] conceptions; namely, that the matter now condensed into the solar system once formed a vast rotating spheroid of extreme rarity extending beyond the orbit of Neptune; that as it contracted its rate of rotation necessarily increased; that by augmenting centrifugal force its equatorial zone was from time to time prevented from following any further the concentrating mass, and so remained behind as a revolving ring; that each of the revolving rings thus periodically detached eventually became ruptured at its weakest point, and contracting upon itself, gradually aggregated into a rotating mass; that this like the parent mass, increased in rapidity of rotation as it decreased in size, and where the centrifugal force was sufficient, similarly through off rings, which finally collapsed into rotating spheroids; and that thus out*

*of these primary and secondary rings arose the planets and their satellites, while from the central mass there resulted the Sun*” [104, p. 201].

Spencer succinctly outlined his thoughts on the Sun when he defended himself in *The Reader*. He opened as follows: “*The hypothesis of M. Faye, which you have described in your numbers for January 28 and February 4, is to a considerable extent coincident with one which I ventured to suggest in an article on ‘Recent Astronomy and the Nebular Hypothesis,’ published in the Westminster Review for July, 1858. In considering the possible causes of the immense differences of specific gravity among the planets, I was led to question the validity of the tacit assumption that each planet consists of solid or liquid matter from centre to surface. It seemed to me that any other internal structure, which was mechanically stable, might be assumed with equal legitimacy. And the hypothesis of a solid or liquid shell, having its cavity filled with gaseous matter at high pressure and temperature, was one which seemed worth considering, since it promised an explanation of the anomalies named, as well as sundry others*” [105]. He continued: “*The most legitimate conclusion is that the Sun is not made up of molten matter all through; but that it must consist of a molten shell with a gaseous nucleus. And this we have seen to be a corollary of the Nebular Hypothesis*” [105].

Throughout the article in *The Reader*, Spencer cited extensively from his prior work [104]. The resemblance to Faye’s 1865 papers [111, 112] was difficult to justify as coincidental. Spencer argued strongly for the existence of convection currents within the Sun: “*... hence an establishment of constant currents from the center along the axis of rotation towards each pole, followed by a flowing over of accumulation at each pole in currents along the surface to the equator; such currents being balanced by the continual collapse, towards the center, of gaseous matter lying in the equatorial plane*” [105]. The presence of convection currents was to become a central aspect of Faye’s model. Nonetheless, Spencer was arguably one of the first to invoke true convection currents within the Sun.

There were several elegant strokes in Spencer’s original paper in the *Westminster Review* [104], including his anticipation of the contraction hypothesis which he re-emphasized in *The Reader*: “*Supposing the Sun to have reached the state of a molten shell, enclosing a gaseous nucleus, it was concluded that this molten shell, ever radiating its heat, but ever acquiring fresh heat by further integration of the sun’s mass, will be constantly kept up to that temperature at which its substance evaporates*” [105]. He advanced two strata of atmosphere above the molten solar surface, the first “*made up of sublimed metals and metallic compounds*” and the second of “*comparatively rare medium analogous to air*” [105].

Spencer was concerned with the specific gravity of the sun, insisting “*but the average specific gravity of the Sun is about one*” [105]. He ventured: “*The more legitimate conclu-*

sion is that the sun's body is not made up of molten matter all through, but that it consists of a molten shell with a gaseous nucleus. . . the specific gravity of the Sun is so low as almost to negative the supposition that its body consists of solid or liquid matter from the center to surface, yet it seems higher than is probable for a gaseous spheroid with a cloudy envelope" [105]. Spencer reached this conclusion because he considered only the specific gravity of the metals and materials on Earth. He never realized that the Sun was mostly made of hydrogen. As such, given his building blocks, Spencer was left with a gaseous interior. The insight was profound. In fact, the objection which Spencer made, with respect to the improbability of a gaseous spheroid, would be repeated by the author, before he became acquainted with Spencer's writings [57].

Specific gravity has become a cornerstone of the modern liquid metallic hydrogen model of the Sun [57–60]. At the same time, science must marvel at the anticipation which Spencer gave of the current gaseous models of the Sun when he wrote: "...but that the interior density of a gaseous medium might be made great enough to give the entire mass a specific gravity equal to that of water is a strong assumption. Near its surface, the heated gases can scarcely be supposed to have so high a specific gravity, and if not, the interior must be supposed to have a much higher specific gravity" [105]. This is precisely what is assumed by astronomy today, as it sets the photospheric density to  $\sim 10^{-7}$  g/cm<sup>3</sup> and that of the solar core to  $\sim 150$  g/cm<sup>3</sup> [57]. With respect to convection currents and intrasolar density, it could be argued that Spencer led astrophysical thought.

Spencer closed his defense by restating his theory of sunspots. He initially advanced that the spots were essentially cyclones and credited John Herschel with the idea [105]. He then stated that cyclones contained gases and that the effects of refraction could account for their dark appearance. Spencer would modify his idea over time, but he continued to focus on cyclones. His conjectures regarding sunspots would have no redeeming features for the current understanding of these phenomena. As such, suffice it to re-emphasize the novelty of Spencer's *Bubble Sun* as a significant departure from the solid model of the period, with the introduction of convection currents and arguments regarding internal solar density.

### 4.3 Angelo Secchi and the partially condensed photosphere

Angelo Secchi [3] first outlined his ideas regarding the physical constitution of the Sun in the *Bullettino Meteorologico dell' Osservatorio del Collegio Romano* in two 1864 manuscripts [95, 96]. John Herschel followed suit in April of the same year [97]. Secchi's January work, represented a gentle rebuttal of Gustav Kirchhoff, initially relative to sunspots: "Signor Kirchhoff rejects both the theory of Herschel and that of Wilson. We will first permit ourselves the observation that it is one thing to refute Herschel's theory, and quite another to

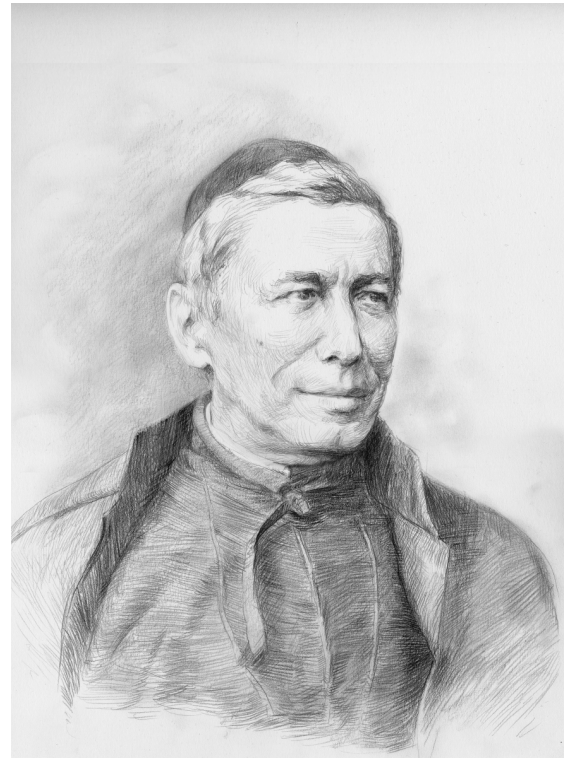


Fig. 2: Father Angelo Secchi, S.J. (June 29th, 1818 — February 26th, 1878), was one of the foremost solar astronomers of his day and the Director of the Observatory of the Roman College. In 1864, Secchi advanced a solar model wherein the photosphere was formed of solid or liquid particulate matter floating on the gaseous body of the Sun [95, 96]. (Drawing by Bernadette Carstensen — used with permission.)

refute Wilson's, and that when the first is laid to rest, the second one hardly collapses" [95]. Secchi also disagreed with Kirchhoff relative to thermal emission, disputing that all objects at the same temperature produce the same light: "Kirchhoff relies greatly on the principle that all substances become luminous at the same temperature in order to prove that the core of the sun must be as bright as the photosphere. Here it seems to us that two quite different matters have been conflated: that is, the point at which bodies begin to excite luminous waves capable of being perceptible to the eye, and the fact that all [substances] at the same temperature should be equally luminous. We can accept the first of these propositions, and wholly reject the second. In furnaces we see gases of entirely different luminosity from that of solids, and the strongest [hottest] flame that is known — that is, that of the oxyhydrogen blowpipe — is it not one of the least luminous?" [95]. In this respect, Secchi was actually correct, as Kirchhoff had inappropriately extended his law to liquids and gases. Secchi realized that gases could not follow Kirchhoff's supposition. This was a rare instance in the scientific literature where the conclusions of Kirchhoff were brought into question. Secchi also expounded on his theory of the

Sun in his classic text [95, p. 37]. Nonetheless, considering Secchi's position, his first article displayed a certain sternness with respect to Kirchhoff, closing with the words: "*We wanted, therefore, to say these things less to object to such a distinguished physicist, than to prevent science from taking a retrograde course, especially since history shows that persons of great authority in one branch of knowledge often drag along, under the weight of their opinion, those who are less experienced, even in matters where their studies are not sufficiently deep and where they should not have such influence*" [95]. Secchi appeared to be arguing, much like Bartholomew [106], that astronomy had become too specialized for the non-professional, even if represented by Kirchhoff himself.

The heart of Secchi's conception of the Sun was outlined in his November 1864 paper [96]. Secchi was concerned with the physical appearance of the solar surface: "*The grid-like solar structure seemed to us to offer nothing regular in those parts of the disc that are continuous, and thus the term granular appears very appropriate. Nevertheless, in the vicinity of the sunspots, that of willow leaf remains justified, because we actually see a multitude of small strips which terminate in rounded tips, and which encircles the edge of the penumbra and of the nucleus, resembling so many elongated leaves arranged all around. The granular structure is more visible near the spots, but it is not recognizable in the faculae; these present themselves like luminous clusters without distinguishable separation, emitting continual light without the interruption of dots or of that black mesh*" [96]. He then clarified his model of the solar photosphere: "*Indeed this appearance suggests to us what is perhaps a bold hypothesis. As in our atmosphere, when it is cooled to a certain point, there exists a fine substance capable of transforming itself in fine powder and of forming clouds in suspension, (water transforming into so-called 'vesicular' vapor or into small solid icicles), so in the enflamed solar atmosphere there might be an abundance of matter capable of being transformed to a similar state at the highest temperatures. These corpuscles, in immense supply, would form an almost continuous layer of real clouds, suspended in the transparent atmosphere which envelopes the sun, and being comparable to solid bodies suspended in a gas, they might have a greater radiant force of calorific and luminous rays than the gas in which they are suspended. We may thus explain why the spots (that are places where these clouds are torn) show less light and less heat, even if the temperature is the same. The excellent results obtained by Magnus, who has proved that a solid immersed in an incandescent gas becomes more radiant in heat and light than the same gas, seem to lend support to this hypothesis, which reconciles the rest of the known solar phenomena*" [96]. Secchi's model differed from Spencer's [104, 105] in that his photosphere was not a continuous layer of liquid. Rather, Secchi's Sun was essentially gaseous throughout. In his photosphere, solid matter was suspended within the gas. Secchi adopted this model as

a result of his visual observations and of Magnus' work on the thermal emission of caustic soda in the transparent gas flame [102]. In this regard, Secchi demonstrated a relatively good understanding of thermal emission.

Over the years, Secchi refined his model of the Sun, but the discussions would be highly centered on the nature of Sun spots. Secchi was a prolific author with more than 800 works to his name [128, p. xvi]. A partial listing of these, compiled at his death, included more than 600 publications [128, p. 95–120]. By necessity, the focus will remain limited to only five of his subsequent contributions on the Sun [114–118].

In the first of these publications [114], Secchi examined sunspots and largely confirmed Wilson's findings [84] that sunspots represented depressions on the solar disk. For both Secchi and Faye, this became a key objection to Kirchhoff's "*cloud model*" of sunspots [43].

In the second article, published in 1868 [115], the astronomer was concerned with the observation of spectral lines in the corona, but he concluded with a defense of the gaseous Sun. Secchi referred to a "*famous objection*" against his model, but never named the source. In actuality, for Secchi, the source of the objection must have been Kirchhoff's *Comptes Rendus* article, which appeared the previous year: "*From the relation which exists between the emissive and absorptive power of bodies, it results in an absolutely certain manner, because in reality the light emitted by the solar nucleus is invisible to our eye, this nucleus, whatever its nature may be, is perfectly transparent, in such a manner that we would visualize, through an opening situated on the half of the photosphere turned in our direction, through the mass of the solar nucleus, the internal face of the other half of the photosphere, and that we would perceive the same luminous sensation as if there was no opening*" [121, p. 400]. Kirchhoff's objection was almost identical to that first leveled by Spencer in 1865 [105, p. 228]: "*But if these interior gases are non-luminous from the absence of precipitated matter must they not for the same reason be transparent? And if transparent, will not the light from the remote side of the photosphere, seen through them, be nearly as bright as that from the side next to us?*" Kirchhoff had strong ties with Guthrie, Roscoe, and the English scientific community. In addition, in light of the previous incident between Kirchhoff and Stewart on priority in thermal emission [61, 138] it is difficult to imagine that the German scientist was unaware of Spencer's work. Two years had already passed.

In response to Kirchhoff, Secchi stated: "*The objection consisted in holding that, if Sun spots were openings in the photosphere, one should be able to see through a gaseous solar mass the luminous photosphere on the other side: as a result, Sun spots would be impossible, since they are not luminous, but black*" [115]. Secchi advanced two lines of defense: "*1) that sunspots, even in their nucleus, are not deprived of light and 2) that for the entire solar mass to be able to produce an absorption capable of preventing the visualiza-*

tion of the other side, it suffices that the interior of the Sun possess an absorbing power identical to its external atmosphere" [115]. Here was perhaps the conclusion of one of the first discussions concerning internal stellar opacity. It reflected why Spencer's complaint was central to the history of astronomy.

Secchi's third work in this series [116] was surprising for two reasons. First, Secchi described that he "*even believes he has seen traces of water vapour in the Sun, especially near the sunspots*" [116, p. 238]. Secondly, and most importantly, Secchi appealed to the French scientific community and to Mr. Sainte-Claire Deville to work on observing the incandescent light emitted by hydrogen under conditions of high pressure [116]. Sainte-Claire Deville immediately followed Secchi's letter with an affirmative response. Secchi thus highlighted the importance of line broadening in hydro- [33–37] for astrophysical thought [116, p. 238].

In the fourth work of this series, Secchi once again argued that "*sunspots are cavities in the photosphere in whose interior the absorbing layer is thicker*" and continues that "*the brilliant lines that often traverse their nucleus could well be the direct lines of that gas which I have signaled constitutes the gaseous mass of the interior of the Sun*" [117, p. 765]. Secchi was completely mistaken, as these lines do not originate from inside the solar body. His 1869 argument [117] was also counter to that which he already outlined when speaking on stellar opacity a year earlier [115].

In the final work of interest, Secchi described four possible aspects of the chromosphere including: "*The first aspect is one of a layer clearly terminated, as would be the free surface of a liquid. . . sometimes, especially in the region of faculae, the surface is diffuse*" [118, p. 827]. Secchi completed his 1872 work with a detailed visual description of prominences.

Secchi also entered into a prolonged confrontation in *Comptes Rendus*, initiated by Lockyer, over the constitution of the Sun (reprinted in [5, p. 500–515]). The arguments were spectroscopic in nature and focused on the photosphere, the reversing layer, and the chromosphere. The rivalry, surrounding the gaseous models, had become intense.

In summary, a detailed review of Secchi's work reveals that he was truly an "observational astronomer". Though his initial contributions on the Sun were devoid of mathematical arguments, he displayed a keen sense of deduction, a broad scientific knowledge, and a profound honesty. Unlike Spencer [104, 105], Secchi did not bring to prominence the presence of convection currents inside his gaseous Sun. He based his solar model on the appearance of the solar surface and the work of Magnus [102]. Secchi opposed Kirchhoff [43] on the appearance of sunspots, correctly arguing for Wilson's cavities [84]. Secchi also disputed Kirchhoff's law [30–32] as experimentally unfounded relative to gases [95]. In his book, Secchi provided a discussion of thermal radiation [3, p. 311–319], reminding us of the work of Melloni who demonstrated that: "*different substances possess a par-*

*ticular and elective absorbing force, each of which acts on different heat rays, absorbing some while permitting others to pass, much like colored media acts on white light*" [3, p. 311]. Herein lays Secchi's objection to the universality of Kirchhoff's formulation [30–32]. He recognized the emphasis of his day on line broadening [33–37] and was one of the first to invoke significant stellar opacity [115]. Unfortunately, he advanced seeing water on the solar surface [116, p. 238]. Eventually, mankind would indeed discover water on the Sun [131], but Secchi and his model, by then, would be long forgotten.

#### 4.4 de la Rue, Stewart, Loewy, Frankland, and Lockyer

Shortly after Secchi published his commentaries in *Bullettino Meteorologico* and in *Les Mondes* [95, 96], Warren de la Rue, Balfour Stewart, and Benjamin Loewy made their famous report on their theory of sunspots on January 26, 1865. Armed with the sunspot observations of Carrington [132], they expanded on his discoveries [133–137]. Carrington led a tragic life [138, p. 117–128] and was an amateur [13, p. 32]. His observational work, unlike Spencer's ideas, became a cornerstone of astronomy. Presumably, this was because Carrington established the differential rotation of the Sun [132]. He also stayed clear of controversial philosophy and of theorizing on the internal constitution of the Sun. As for de la Rue, Stewart, and Loewy, their contributions with the photoheliograph at Kew were significant. As professional scientists, they ventured into a discussion on the constitution of the photosphere. Historically, their classic paper [133], like Faye's [111, 112], also appeared immediately after the *Les Mondes* translation of Secchi's seminal work [96].

Nonetheless, de la Rue, Stewart, and Loewy were the first [133] to propose that the continuous solar spectrum was consistent with a *fully* gaseous atmosphere. They were quickly endorsed by Frankland and Lockyer who, after believing they had disarmed Kirchhoff, wrote: "*That the gaseous condition of the photosphere is quite consistent with its continuous spectrum. The possibility of this condition has also been suggested by Messrs. De la Rue, Stewart, and Loewy*" [37]. The argument was based on the existence of pressure broadening, observed with hydrogen under conditions of high pressure [37]. It was here that pressure broadening became permanently linked to the gaseous models of the Sun. However, the idea of a fully gaseous photosphere would not truly take hold until much later. For most scientists, the photosphere continued to have at least traces of condensed matter. As for the concept that hydrogen, under pressure, could create a Planckian blackbody spectrum, it was always erroneous. Gases could never produce the required emission [77]. Frankland and Lockyer could not have established this fact with the experimental methods of 1865. They merely observed that the hydrogen lines became considerably broadened, completely unaware of their incorrect lineshape. Irrespective of this shortcoming, the paper by Frankland and

Loewy impacted scientific thought for the rest of the century and became highly cited by the astronomical community. As such, Frankland and Lockyer, along with de la Rue, Stewart, and Loewy who had so magnificently photographed the Sun, hold a preeminent role in the history of solar science [37, 133–137].

Addressing faculae, de la Rue and his team reported: “*It would thus appear as if the luminous matter being thrown up into a region of greater absolute velocity of rotation fell behind to the left; and we have thus reason to suppose that the faculous matter which accompanies a spot is abstracted from that very portion of the sun’s surface which contains the spot, and which has in this manner been robbed of its luminosity*” [134]. Based on such observations, they ventured: “*From all of this it was inferred that the luminous photosphere is not to be viewed as composed of heavy solid, or liquid matter; but is rather of the nature either of a gas or cloud, and also that a spot is a phenomenon existing below the level of the sun’s photosphere*” [134]. The proposal resembled Secchi’s [95, 96]. With these words, Kirchhoff’s thermodynamic reasoning, regarding the continuous solar spectrum, became supplanted by visual observations and the Sun adopted the gaseous state.

Given Stewart’s earlier conflict with Kirchhoff [61, 139], it would not be unexpected if the Scottish astronomer, at the side of de la Rue and Loewy, had agreed to dispense with Kirchhoff’s condensed photosphere [133–135]. However, this was not to be the case. Stewart, a man of strong moral character [140, 141], immediately abandoned de la Rue’s gaseous sun, as we will come to discover in Section 4.7.

Beyond Stewart, a historical review of the period reveals that virtually every prominent astronomer voiced public disapproval of Kirchhoff’s liquid photosphere. In a real sense, Kirchhoff stood essentially undefended against much of the scientific community. Yet, were the arguments of men like Secchi, Faye, de la Rue, and Lockyer truly sufficient to eventually advance a fully gaseous photosphere? Note in this regard, the *faux pas* by de la Rue, Stewart, and Loewy as to the cause of sunspots in their very next paper: “*the behavior of spots appears to be determined by the behavior of Venus*” [134]. Though Kirchhoff might have misjudged the nature of sunspots, the fault was minor and irrelevant today when compared to the error of assigning an improper phase to the entire Sun. In this respect, Galileo’s words in his first letter to Welser come to mind: “*For the enemies of novelty, who are infinite in number, would attribute every error, even if venial, as a capital crime to me, now that it has become customary to prefer to err with the entire world than to be the only one to argue correctly*” [101, p. 89].

#### 4.5 Hervé Faye and loss of the solar surface

Hervé Faye opened his classic presentation on the constitution of the Sun on January 16th, 1865, by stating that the solar phenomena had been well popularized [103]. Therefore, he



Fig. 3: Hervé Faye (October 1st, 1814 — July 4th, 1902) was a prominent French astronomer with a distinguished career in science and public service as a minister of education. In early 1865, Faye echoed Secchi’s solar model wherein the photosphere was formed of solid or liquid particulate matter floating on the gaseous body of the Sun [111, 112]. (Drawing by Bernadette Carstensen — used with permission.)

reduced his historical discussions to the strict minimum and limited himself to the simple analysis of current facts and conjectures [111]. He set the stage by recalling the gaseous envelope and the polarization arguments of Arago [111, p. 92–93]. At the same time, he recognized the importance of Kirchhoff’s spectroscopic studies and wrote: “*But incandescent solids and liquids alone give a continuous spectrum, while the gases or the vapors supply but a spectrum reduced to only a few luminous rays*” [111, p. 93]. Faye then argued against Kirchhoff’s view of sunspots, as rejected, even by Galileo [111, p. 94]. He proposed that sunspots were produced by clearings in the photosphere, thereby exposing the nucleus of the Sun. Interestingly, Faye argued for the oblateness of the Sun based on the fluidity of the photosphere. Unfortunately for him, the slight oblateness of the Sun [142] supported a condensed photosphere, not one with a gaseous composition [57]. In his seminal communication [111], Faye did not actually advance a complete solution for the nature of the photosphere. He reserved this critical step for his second paper [112].

Throughout his first work [111], Faye cited many notable figures, but failed to mention either Magnus or Spencer and,

more importantly, Secchi's model [111]. Faye studied under the tutelage of François Arago who, as discussed in Section 3.3, visualized a divide between professional astronomy and popular thought, even in the first half of the 19th century. As such, Bartolomew's arguments for the failure to cite Spencer might be given some weight [106]. But what of Faye's failure to mention Secchi's model?

Secchi was an established scientist and well recognized throughout the western world, especially in Roman Catholic France. Secchi's first Italian paper in the *Bullettino Meteorologico* had already been published for nearly one year [95] by the time Faye gave his address [111]. Secchi's second paper on the constitution of the photosphere was immediately translated into *Les Mondes* by l'Abbé Moigno. It appeared in Paris on December 22nd, 1864 [96]. This was nearly one month prior to Faye's presentation before l'Académie des Sciences on January 16th. Faye's first paper was silent on this point. Nonetheless, in his second paper, presented on January 25th of the same year, Faye reported that "*I have seen, a few days ago, a correspondence by Father Secchi, who has much too studied the Sun to share the popular view reigning today on the liquidity of the photosphere, that our corresponding scientist has arrived from his side to an explanation of sunspots founded on the same principle*" [112, p. 146]. The footnote in Faye's sentence referred to Moigno's translation of Secchi's second paper [96].

Faye's second paper began with a discussion of solar rotation and particularly of the work of Carrington [112, p. 140–142]. He then discussed Helmholtz' contraction hypothesis [112, p. 143] and highlighted the enormous temperatures inside the Sun as a cause of the complete dissociation of its constituents. These gases rose to the solar exterior where they condensed into non-gaseous particles susceptible to incandescence. Faye reasoned that the formation of the photosphere was simply a consequence of the cooling of internal gases [112, p. 144]. He reconciled Arago's argument on polarization with Kirchhoff's need for a continuous spectrum [112, p. 145]. In so doing, he advanced a photosphere based essentially on Secchi's model when he described: *incandescent particles, floating on a gaseous medium*" [111, p. 145]. Faye then highlighted that sunspots were produced by the visualization of the gaseous solar interior [112, p. 146]. This became the source of Spencer's "famous objection" in *The Reader* [105] and reflected Faye's incomplete comprehension of thermal emission.

Faye closed his second paper with an elaborate description of the vertical convection currents which he postulated were present inside the Sun. He replayed much of Spencer's ideas on the Nebular hypothesis and solar cooling. The Frenchman stated that, given sufficient time, the photosphere would become very thick with the "*consistence of a liquid or a paste*". Herein, he directly linked his ideas to Spencer's liquid photosphere [104]. Hence, along with the arguments based on convection currents, Faye introduced another source

of priority claims for the British scholar. Faye's initial exposition [111, 112] was more extensive than Secchi's [95, 96], but not significantly superior to Spencer's [104, 105].

Once his papers on the Constitution of the Sun were presented to the Académie, Faye published a slightly different work in *Les Mondes* [143] in which he again stated that Father Secchi arrived at the same conclusion regarding the photosphere. The Frenchman sought Secchi's approbation [143, p. 298]. As for Secchi, he gallantly responded to Faye's *Les Mondes* article in a letter published in *Comptes Rendus*, on March 6th, 1865 [144]. Secchi wrote in most charitable terms, as if delighted by Faye's claim of simultaneous discovery. If anything improper had occurred, it was silently forgiven. A few years later, in 1867, Secchi would receive *la croix d'officier de la Légion d'Honneur* from the hand of Napoleon III [128, p. iii, 208].

Faye first addressed the sunspot problem in his model within his third paper on the constitution of the Sun, published in 1866 [120]. He began the discourse by praising English astronomy and citing every prominent British astronomer of the period, including Herschel, Carrington, Dawes, Nasmyth, Stone, Huggins, de la Rue, Stewart, Thomson, and Waterston. Spencer was absent from the list. Still, the focus of Faye's work was a direct address of Spencer's complaint with respect to solar opacity: "*The difficulty is relative to the explanation of sunspots. We know that gases heated to the point of becoming luminous never rise to the point of incandescence; the latter being a property of solid particles, even when they are reduced to the same tenuousness*" [120]. Faye restated Secchi's idea that the photosphere was made of fine condensed incandescent particles floating in a gaseous medium. If these particles were missing from a region, it would necessarily become obscure. This was his explanation of sunspots: regions devoid of these incandescent particles. Faye then raised the "famous objection", without mentioning Spencer's name, as if the charge had come from nowhere: "*In this we object that if gases emit but little light, by consequence they are transparent. If then an opening was made in the photosphere, one should see, across the gaseous internal mass of the Sun, the opposite region of the same photosphere with a brilliance barely diminished; as a result there would no longer be any spots*" [120]. It was only later, in 1867, that Faye was finally forced to acknowledge Spencer as a source of the complaint [122, p. 404]. He did so in a footnote, while insisting that the reproach had first been brought to his attention by the editor of *Comptes Rendus*. This was the most assured means of preventing impropriety. In the same work, Faye remained silent on Spencer's convection currents, variations in solar density, and justified priority claim for a gaseous solar interior.

Faye addressed the complaint by arguing that, in fact, it was a property of gases or vapors to extinguish light as well as an opaque body, provided that the thickness of the gas was sufficient. Faye was essentially invoking optical thick-



ness and, once again, foreshadowing the modern stellar opacity problem. In answering Secchi [144], Faye presented his idea that the interior of the Sun could be viewed as concentric layers of gas [145, p. 296]. The thought was to remain associated with the treatment of the internal constitution of the Sun and was also used by Eddington in advancing his theoretical treatment of the problem [19].

As for Faye's debate with Kirchhoff, it was less than cordial. The battle began when Faye improperly described Kirchhoff's model in the literature [120]. Kirchhoff would rebuke Faye for maintaining that horizontal convection currents did not occur at the level of the photosphere: "*Mr. Faye then rejects the existence in the solar atmosphere of horizontal currents which, in my hypothesis, must explain the different movements of sunspots*" [121, p. 398]. Unlike Kirchhoff, Faye invoked internal convection currents with a vertical displacement. On the surface of the Sun, he wanted voids to obtain the spots, not horizontal currents [122, p. 403]. Faye responded to the father of spectral analysis in the most inappropriate tone: "*I congratulate myself in having received a personal intervention from Mr. Kirchhoff, because his letter explains to me something of which I have always been profoundly astonished, to know the persistence with which a man of such high merit can sustain a hypothesis so incompatible with the best known facts*" [122, p. 401]. Faye, of course, referred to Kirchhoff's cloud model of sunspots. In any case, Faye's arrogance in the published article was met eventually by a sound defeat at the hand of Kirchhoff [124].

Faye was so concerned by Kirchhoff's first letter of objection that he drafted a second response, which was mathematical in nature [123], even before the German had the opportunity of reply to his first answer [122]. In this letter, the Frenchman invoked that the nature of sunspots was similar to the darkened grid associated with solar granulation. He went on to dispute, like his mentor Arago (see Section 3.3), the existence of the corona [123]. Both statements were erroneous. Then, Faye opened a new line of defense for his sunspot theory and the controversy relative to seeing through the Sun. He believed that he could counter Kirchhoff and Spencer by advancing that the gas density inside the Sun was not homogeneous. He began by arguing that the interior of the Sun was highly variable in density [123, p. 222–223]: "*In consequence this central density must be many hundreds or even thousands of times superior to that of the superficial layer which forms the photosphere*". Once again, he failed to credit Spencer, this time regarding varying internal solar densities [105]. Faye then proposed a gaseous internal medium which could be viewed as spherical layers of material [123, p. 222–223]. He advanced the same idea a year earlier during a discussion with Father Secchi [146]. The concept has remained in astronomy to the present.

Finally, Faye made his critical misstep. He invoked that a ray of light which hit the higher density of the mass inside the Sun was refracted inward and unable to escape. The as-

tronomer then audaciously charged Kirchhoff with failing to understand the consequences of a non-homogeneous solar interior.

Kirchhoff was severe in his defense. Using his law of thermal emission, Kirchhoff disarmed Faye. He reminded the scholar that the radiation inside an opaque enclosure must be black [124]. As such, Kirchhoff was, ironically, the first person to postulate that the radiation inside a gaseous Sun, surrounded by an enclosing photosphere, must be black. In reality, Kirchhoff's conclusion was only partially correct. The solar photosphere produced a thermal spectrum. However, it was not truly black, since the Sun maintained convection currents which prevented this possibility. Nonetheless, if the photosphere was condensed and perfectly enclosed a gaseous solar body, then that interior would have to contain the same thermal radiation as emitted on the solar surface. Still, Kirchhoff was mistaken in believing that the radiation would have to be black. It would take many years before this reality became apparent [61–66]. In any case, Kirchhoff's arguments, though not completely sound, well surpassed Faye's physical knowledge of the problem. With time, the modern theory of the Sun eventually applied Kirchhoff's ideas to the problem of internal stellar opacities. In doing so, it removed the condensed nature of the photosphere as a primary source of photons. Therefore, there was a great difference between the problem addressed by Faye and Kirchhoff and the current gaseous models of the stars. Kirchhoff and Faye were dealing with photons produced initially by condensed matter in the photosphere. The modern theory holds that such photons could be generated in the solar core, without recourse to condensed matter and without having the Sun enclosed by its condensed photosphere.

The great battle between Faye and Kirchhoff over the nature of sunspots and the solar constitution would end with a whimper. Faye advanced [125] that Kirchhoff had abandoned his model, because the German failed to defend it in his rebuttal letter [124]. Kirchhoff retorted by emphatically arguing that he continued to defend his solar theory [126].

As for Faye, he was completely unable to respond to Kirchhoff's closing argument on the presence of blackbody radiation inside a gaseous solar model. In 1872, he finally abandoned his first theory of sunspots, replacing it with cyclonic formation, an idea for which he once again failed to credit Spencer. Yet, in closing the openings he had created in the photosphere, Faye finally referred to Spencer [119] for his "famous objection". By this time, the problem of internal solar opacity had become irrelevant. Mankind became, at least for the moment, theoretically unable to "see within the Sun". The fully gaseous models, advanced in the 20th century, reintroduced the concept that scientists could visualize differing depths within the Sun. Despite the lack of the enclosure, as required by Kirchhoff in his 1867 letter [124], the modern solar interior has been hypothesized to contain blackbody radiation [15–17].

As a point of interest, the differences between Faye's, Secchi's, and Lockyer's concepts of sunspots have been reviewed in the 1896 version of Young's classic text [8, p. 182–190]. Today, nearly all of these ideas have been abandoned. Much of the controversies which called for the dismissal of Kirchhoff's condensed photosphere have long ago evaporated. The Wilson effect alone remains [84], as a standing tribute to that great English astronomer, who unlike Faye and many of his contemporaries, was so careful relative to queries and conjectures.

#### 4.6 Discord, stellar opacity, and the birth of the gaseous Sun

Imagine a gaseous Sun. The idea was so tantalizing for men of the period that it became a source of instant quarrel for priority. Secchi gently rebuked Kirchhoff [95], absolved Faye [144], and defended himself against Lockyer [5, p. 500–515]. Faye, in turn, battled with Kirchhoff [121–127] and after securing the blessing of Father Secchi [144], was quick to announce his innocence before the Académie: “*This letter [from Secchi] demonstrates that we followed at the same time, Father Secchi and I, a train of ideas which was altogether similar...*” [145, p. 468]. Like his English counterparts, Faye acted as if he was also unaware of John Herschel's 1864 article [97]. But what could be said of this coincidence of ideas? Was it really possible that, in the span of a few months, Secchi, Herschel, Faye, Lockyer and Frankland, and de la Rue along with Stewart and Loewy all independently conceived of the same idea? Faye addressed the question: “*With respect to the analogies that Father Secchi signals with reason between his ideas and mine, coincidences of this type offer nothing which can surprise, identical ones [ideas] are produced every time that a question is ripe and is ready for a solution*” [145]. But surely, the argument could not be extended to every prominent astronomer of the period. Being first and very likely ignorant of Spencer's English text [104], only Secchi could claim truly independent thought.

After hearing from the Jesuit astronomer, Faye finally cited Magnus [145, p. 471], the scientific element which was central to his model, but which, unlike Secchi, he had so neglected in his earlier works. However, if one accounted for Spencer's and Secchi's ideas in Faye's famous papers [111, 112], there was not much left as original thought. The most significant exception was Faye's idea that the photosphere of the Sun was devoid of a real surface [13, p. 42], also advanced in *Les Mondes* [143]. Faye believed that the “*presence of the photosphere does not interrupt the continuity of the [central] mass*” of the Sun [143, p. 301] and insisted that “*This limit is in any case only apparent, the general milieu where the photosphere is incessantly forming surpasses without doubt more or less the highest crests or the summits of the incandescent clouds*” [143, p. 298]. Such was the first consequence of the gaseous models: there could be no defined solar surface. The problem continues to haunt astrophysics to this day [57, 146].

With Faye, the Sun lost its distinct surface.

It is evident that Faye never properly acknowledged Spencer [120, p. 235]. Nonetheless, he remained delighted that his works had been immediately reviewed in *The Reader* by Lockyer, as evidenced by his 1865 letter [145]. As such, it is doubtful, as early as 1865, that he never knew of Spencer's rebuttal [105]. Faye behaved as if concerns against his “*transparent solar interior*” originated exclusively from Kirchhoff as late as 1866 [121]. In fact, it was clear that the criticism of seeing through the Sun had been swiftly leveled by Spencer [105, p. 228]. Since Kirchhoff was a friend of Roscoe [61], it was not unlikely that he quickly became aware of *The Reader* series. Once again, Spencer wrote: “*But if these interior gases are non-luminous from the absence of precipitated matter must they not for the same reason be transparent? And if transparent, will not the light from the remote side of the photosphere, seen through them, be nearly as bright as that from the side next to us?*” [105, p. 228]. Meadows argued that this criticism of Faye's work originated from Balfour Stewart [13, p. 41–42], but did so without citation. In fact, the reference to Balfour Stewart was provided by Norman Lockyer, when he reprinted his letters, in 1874, and added a footnote giving credit to Balfour Stewart over Kirchhoff [5, p. 57], well after Spencer made his case. This was how Lockyer distorted the scientific record using a footnote: “*This note was added to the article as it originally appeared, as the result of a conversation with my friend Dr. Balfour Stewart. I am more anxious to state this, as to him belongs the credit of the objection, although, as it was some time afterwards put forward by Kirchhoff, the latter is now credited with it, although it was noticed by Faye, Comptes Rendus, vol. lxxiii, p. 235, 1866. The idea is this: — If the interior solar gases are feeble radiators, then, on the theory of exchanges, they must be feeble absorbers; hence they will be incompetent to absorb the light coming through the hypothetically gaseous Sun from the photosphere on the other side (1873)*” [5, p. 57]. One can only wonder why the discoverer of Helium, one of the great fathers of spectral analysis, and the founder of the journal *Nature*, insisted on altering the historical record. Apparently, Spencer was not as weak in thermodynamics, as previously argued [106].

#### 4.7 Stewart, Kirchhoff, and amateurs

Stewart had been an author on the initial paper with de la Rue and Loewy [133–135]. But suddenly, he detached himself from this position when he discussed the photosphere, without invoking the presence of a gas: “*Next with regard to the photosphere or luminous envelope of the Sun, this surface, when viewed through powerful telescopes, appears granulated or mottled... But besides this there is reason to believe that great defining as well as magnifying power discloses the fact that the whole photosphere of the Sun is made up of detached bodies, interlacing one another, and preserving a great amount of regularity both in form and size*” [147]. Thus, when Stewart wrote independently, it was obvious that he ac-

tually believed that the photosphere was a liquid or solid. In this respect, he became aligned with Spencer and Kirchhoff on the condensed nature of the photosphere.

In his *Lessons in Elementary Physics*, Stewart persisted in breaking from de la Rue and Loewy [148, p. 279]. This was the case even in the edition published closest to the end of his life. In this classic text for its day, Stewart stated: “*If we throw upon the slit of our spectroscope an image of the Sun or of one of the stars, with the view of obtaining its spectrum, we find a large number of black or dark lines in a spectrum otherwise continuous, and we argue from this that in the Sun or stars we start with a solid or liquid substance, or at any rate with some substance which gives us a continuous spectrum, and that between this and the eye we have, forming a solar or stellar atmosphere, a layer of gas or vapours of a comparatively low temperature, each of which produces its appropriate spectral lines, only dark on account of the temperature of the vapours being lower than that of the substance which gives the continuous spectrum*” [148, p. 279]. Again, there was no mention of a gaseous photosphere supporting condensed matter precipitates in this description of the problem. In fact, this passage echoed Kirchhoff’s explanation [43], as Stewart was all too aware of the nature of thermal emission in gases [149].

Hence, the Scottish physicist very much desired that the photosphere be condensed, as evidenced initially in his 1864 article: *On the Origin of Light in the Sun and Stars* [150]. In this work, Stewart advanced that planets could alter the brightness of stars by modifying the amount of sunspots. He tried to answer the question “*From all this it is evident that in the case of many stars we cannot suppose the light to be due to an incandescent solid or liquid body, otherwise how can we account for their long continued disappearance?*” [150, p. 452]. The entire manuscript was aimed at accounting for this disappearance, even if the photosphere was solid or liquid. He stated in this regard “*if it can be proved, as we think it can, that a disc full of spots is deficient in luminosity*” [150, p. 452]. Stewart made this conjecture to explain the occurrence of variables [150]. For him, the photosphere had to be liquid or solid. But variable stars posed a tremendous scientific difficulty. As a result, he required something like planets to modify their emission cycles [150]. Stewart reconciled his desire for a liquid or solid photosphere within these types of stars by stating: “*the approach of a planet to the Sun is favourable to luminosity*” [150, p. 454]. His desire for condensed matter was so powerful that Stewart advocated the scientific error that Venus itself can modify the appearance of sunspots [150, p. 454]. Regrettably, Stewart would eventually discover Loewy’s misconduct while producing mathematical reductions relative to the work at Kew [151, p. 361]. This would place a considerable tarnish on the Kew group, and Stewart would never again speak on planetary effects relative to sunspots.

Earlier, in *Origin of Light* [150, p. 450–451] Stewart had viewed sunspots as cavities on the Sun, produced by an open-

ing in the photospheric matter revealing the dark nucleus of the interior. In 1864, just prior to the paper with de la Rue and Loewy, Stewart stated that the Sun possessed with a solid body [150, p. 451]. The concept was similar to Wilson [84].

Despite Loewy’s misconduct [151], Stewart could not long maintain a fully gaseous photosphere, given his extensive knowledge of thermal emission in gases [149]. Clearly, he had not embraced de la Rue’s model [133–135] and the claim by Lockyer, discussed in Section 4.7, that the photosphere could be completely gaseous and devoid of any condensed matter [37]. On the same note, Stewart’s entire discussion on thermal radiation, in his classic physics text, is well worth reading [148, p. 270–297]. It revealed his profound knowledge of such processes and also his understanding that gases cannot produce the continuous spectrum required.

Stewart maintained support for what is essentially Kirchhoff’s liquid photospheric model. He did so despite his previous adversity with the German [61, 139]. In this regard, he was being guided by the same scientific reasoning as his former detractor [43]. The Scottish scientist also held profound values [140, 141, 150]. As such, it is comforting to notice how, in some sense, the two men were now reconciled. Stewart’s continued support for Kirchhoff’s condensed photosphere, was astounding as it *de facto* dismissed any previous arguments relative to Andrew’s critical temperature [28] and line broadening [37]. For Stewart, the primary determinant of the phase of the photosphere was its thermal emission. The same held true for Kirchhoff. Yet, Stewart’s insistence was important because it continued well after critical temperatures and line broadening had entered the halls of astronomy. Those who maintained that the photosphere was gaseous, therefore, continued alone on their journey. They marched on without the support of the two great experts in thermal radiation: Gustav Kirchhoff and Balfour Stewart.

As for Spencer, if there was any merit in his work, other than his obvious and justified claim of priority, it was that he foresaw internal convection currents, variable solar density, and the tremendous problem of internal stellar opacity. The last of these, contained in the “famous objection”, remains a key problem with the idea of a gaseous Sun, despite all attempts to rectify the situation [69, 70]. But what is most fascinating about this philosopher, remains his amateur status in astronomy. Karl Hufbauer has commented on the contributions of amateurs to astrophysics [152]. Bartholomew argues as though there was little room for Spencer and his theoretical ideas in solar science [106]. In this regard, he stands in profound opposition to George Hale, one of the greatest solar observers and the founder of the *Astrophysical Journal*. In 1913, Hale defended the special place of amateurs in astronomy when he drafted the moving obituary of Sir William Huggins: “*If it be true that modern observatories, with their expensive equipment, tend to discourage the serious amateur, then it may be doubted whether the best use is being made of the funds they represent. For the history of sci-*

ence teaches that original ideas and new methods, as well as great discoveries resulting from the patient accumulation of observations, frequently come from the amateur. To hinder his work in any serious way might conceivably do a greater injury than a large observatory could make good... Every investigator may find useful and inspiring suggestions in the life and example of Sir William Huggins. Their surest message and strongest appeal will be to the amateur with limited instrumental means, and to the man, however situated, who would break new ground" [153].

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### Dedication

This work is dedicated to my youngest son, Luc.

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